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Multichannel detector for ion temperature determination in vacuum ultraviolet spectrum

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A vacuum ultraviolet spectrometer equipped with a charge coupled device and an open multichannel plate has been used to analyze the temperature of carbon and oxygen ions in the NOVA-UNICAMP tokamak. The detection system was optimized and aligned to minimize the instrumental broadening. Also, higher order diffractions of the emissions were analyzed, resulting in lower experimental errors. The ion temperature was monitored during the tokamak discharge, presenting values between 30 and 70 eV. © *2007 American Institute of Physics.* [DOI: 10.1063/1.2742811]

Recent studies, such as correlating the ion temperature with transport in tokamaks,[1] show that ion temperature monitoring systems are still important to be developed.[2–4] The traditional method to determine this parameter is the measurement of ion line Doppler broadening[3–6] and, more recently, charge exchange spectroscopy.[1] In the fusion devices, the analysis of core temperatures has been performed using x-ray radiation.[6] However, the measurements using vacuum ultraviolet (VUV) and/or visible radiation are still important since the main impurity ion in many tokamaks is carbon,[5,7] which has emission lines in these spectra. Also, the plasma study of edge regions (or divertor) does not require high energy emissions, so VUV and visible emissions are suitable for this task.[3–5,7] However, the Doppler broadening in the VUV spectrum is lower than in the visible spectrum, increasing the experimental errors. The use of a higher resolution spectrometer can be a solution, but it leads to a decrease of the detected spectra. So, the optimization of medium resolution spectrometers for accurate VUV line broadening measurements is still a subject of interest.

In this article, the setup of a multichannel detector for ion temperature measurements in VUV is discussed. The instrumental broadening was minimized by adjusting the detector rotation and calculated *in situ* using higher order diffractions measurements. Finally, the ion temperature behavior of different impurities during the discharge was obtained.

A McPherson 225 spectrometer was used for these experiments. This spectrometer is a normal incidence device ($\sim 82.5°$) and has only a concave grating (Al/MgF_2 covered) with 1 m focus (Rowland circle diameter). Using a 1200 grooves/mm grating (dimensions 96×56 mm^2) the spectrometer covers the range 500–3000 Å and has 8.3 Å/mm dispersion.[8] The multichannel plate (MCP) (XSI Instruments) has a diameter of 40 mm and is coated by a CsI film to convert VUV photons into electrons. The MCP channels are separated by 12 μm and have a 10 μm diameter each. At its back, there is a phosphor screen (with an independent power supply) to convert the electrons in photons. The charge coupled decive (CCD) (Andor Technology) has 1024×256 pixels, and each pixel is 26×26 μm^2. A reducing coherent glass fiber array was used to couple the MCP to the CCD. This system can measure a 330 Å interval at once, with ~ 0.3 Å/pixel. The spectrometer is connected with the NOVA-UNICAMP tokamak using a 1 in. diameter and 5 m long tube pumped by an independent turbo pump. This tokamak is a small machine with 6 cm minor radius, 30 cm major radius, 10–12 kA plasma current, and 10–15 ms discharges.[9] Due to its small size, no measurements with spatial resolution were performed.

A sketch of the multichannel system is shown in Fig. 1. Besides the MCP and the CCD (both in gray in Fig. 1), there are adapter pieces to fix the detectors and the glass fibers for light coupling. The connection of the glass fibers is one of the critical steps of the setup since light can spread between them, decreasing the system resolution. Other systems employ lens in the place of the fiber optics, but the decrease in the light intensity can be substantial.[4] In our system, the adapter piece between the MCP and CCD is adjusted to guarantee a good light coupling.

After a proper connection of the glass fibers, the alignment of the detector with the spectrometer grating should be done accurately. This is done by adjusting the detector in the directions x, ϕ, and θ (Fig. 1) and minimizing the broadening of some measured plasma emissions. Firstly, the adapter piece which assembles the system in the spectrometer moves the whole piece in direction x, adjusting the focus. A micrometer in the top adjusts the rotation of the system in the ϕ direction using the bellows of the adapter. Combined with the previous adjust, most of the MCP surface can be set in the grating focus. Actually, since the MCP is planar and the grating focus follows the Rowland circle, the whole MCP surface cannot be set in the focus. A final adjust was performed for the system rotation in the θ direction. This is an important issue: if the CCD is not perfectly aligned, the signal can be broadened in full vertical binning measurements, a fact already observed in other devices.[6] To guarantee that a given wavelength falls in the same column for all pixels, the rotation of the system should be better than 0.1°.

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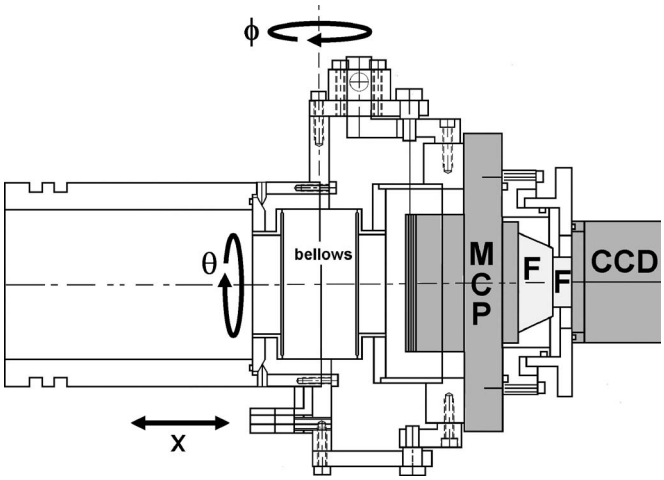

FIG. 1. Multichannel detector system with the MCP and CCD (both in gray), adapter pieces (white), and the glass fibers (F).

After all the adjustments, the instrumental broadening ($\Delta\lambda_{ins}$) should be determined. However, a routine check of $\Delta\lambda_{ins}$ is desired (to check for misalignments). So, tokamak discharges with very low power (and temperature lower than 15 eV) were chosen for this purpose.[8] The Doppler broadening ($\Delta\lambda_D$) is related to the ion temperature (T, in eV) by the equation

$$T = 1.69 \times 10^8 M \left(\frac{\Delta\lambda_D}{\lambda}\right)^2, \tag{1}$$

where M is the ion mass and λ is the line wavelength. In order to discount $\Delta\lambda_{ins}$ from the measured broadening ($\Delta\lambda_{meas}$), the following equation is used:

$$(\Delta\lambda_{meas})^2 = (\Delta\lambda_D)^2 + (\Delta\lambda_{ins})^2. \tag{2}$$

As can be seen by Eq. (1), the Doppler broadening can be minimized if the temperature and the measured wavelength are small and/or the ion mass is high. Figure 2 presents the line broadening measurements of the OIV 787.7 Å and OV 629.7 Å emissions (where OIV indicates the oxygen ion with a charge +3 and OV the oxygen ion with a charge +4), compared with the $L\alpha$ 1215.7 Å broadening. The measurements were performed in low power discharges using a 40 μm slit. As can be seen, the $L\alpha$ broadening is higher since the hydrogen atom is lighter and the wavelength is higher. Also, both OV and OIV ions presented very similar broadening, showing that the measured broadening is very close to the instrumental broadening (if the Doppler broadening would be important, different values should be obtained). Another check was performed using the $L\alpha$ measured broadening. Considering the OV and OIV broadening as being $\Delta\lambda_{ins}$, the hydrogen temperature was calculated, given values of 5–6 eV (a reasonable value). Finally, the figure shows the effect of the planar MCP surface. Lowest broadenings are achieved in the central region of the detector, whereas the edges have a lower resolution. The following ion temperature measurements were performed using a 30 μm slit, presenting an instrumental broadening in the central region of 0.55 Å.

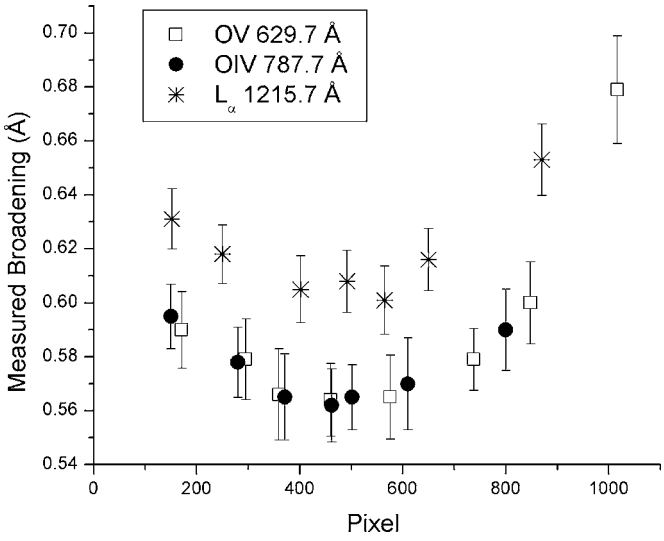

FIG. 2. Measured broadening for different emissions across the detector matrix. Spectrometer slit=40 μm.

With the multichannel system installed and characterized, measurements of the ion temperature were performed. The use of high order diffraction has some advantages. Firstly, the spectrometer dispersion increases with the diffraction order, leading to more accurate broadening measurements. Secondly, the appropriate choice of the diffraction order allows the simultaneous measurement of several emissions in the same tokamak discharge, such as CIII 977.0 Å (measured at third order), CIV 1550.7 Å (second order), and OVI 1037.6 Å (third order), with all emissions measured using only the central half of the detector. Other measured emissions were OV 629.7 Å (fourth order) and OIV 787.7 Å (third order). Finally, the high order diffraction measurements allow an *in situ* check of the instrumental broadening. As an example, for the first and second diffraction orders,

$$(\Delta\lambda_{meas1})^2 = (\Delta\lambda_D)^2 + (\Delta\lambda_{ins})^2, \tag{3}$$

$$(\Delta\lambda_{meas2})^2 = (2\Delta\lambda_D)^2 + (\Delta\lambda_{ins})^2, \tag{4}$$

where $\Delta\lambda_{meas1}$ and $\Delta\lambda_{meas2}$ are the measured broadenings for the first and second diffraction orders, respectively. The factor of 2 in the second equation is due to the second order diffraction. With these two measurements, $\Delta\lambda_D$ and $\Delta\lambda_{ins}$ can be determined. These measurements allow the check, during the measurement, if any factor misaligned the system. This is a very good option since there are several factors which could lead to a misalignment.

As an example, the first two CIV 1550.7 Å diffraction orders were measured. Using the previously measured instrumental broadening (0.55 Å for a 30 μm slit), the temperature was determined as 44±19 eV (first order) and 45.8±9.4 eV (second order). Note that higher diffraction orders lead to higher resolution measurements, decreasing the experimental errors. Then, Eqs. (3) and (4) were solved for these measurements, resulting in $\Delta\lambda_{ins}$=0.547 Å and T=47.1 eV. Note that this value is slightly higher than that measured for each diffraction order. The reason is that the comparison of both measurements allowed a more accurate determination of the instrumental broadening. Similar checks were performed for other emissions. The CIII 977.0 Å line measurement at different orders led to the following temperatures: 33±24 eV (first order), 31.8±7.5 eV (second order), and 30.8±4.5 eV (third order). Using Eqs. (3) and (4), the mean obtained values are $\Delta\lambda_{ins}$=0.552 Å and T=29.5 eV.

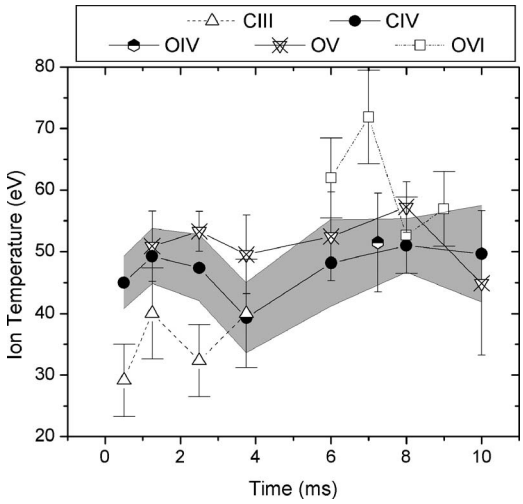

FIG. 3. Measured ion temperatures during the discharge.

Using the CIII 977.0 Å, CIV 1550.7 Å, OIV 787.7 Å, OV 629.7 Å, and OVI 1037.6 Å emissions, the ion temperature measurements were performed during the tokamak discharge. A 250 μs gate was used to trigger the MCP. Some ion temperatures were not measured during the whole discharge. As an example, the OVI temperature was only determined for times higher than 6 ms since these ions are almost absent in the beginning of the tokamak discharge. The results can be observed in Fig. 3. To avoid confusion with the error bars, the CIV error is shown as a gray area. As can be seen, the ion temperature is roughly constant during the discharge, with a small increase in the first milliseconds. The difference among the temperature values is small. The reason is the small size of the tokamak. In this situation, the ions are not separated in shells, such as in bigger tokamaks, and cover a wide region inside the chamber. Anyway, such as expected, a small increase of the temperature with ionization degree is observed: $T_{\mathrm{CIV}} > T_{\mathrm{CIII}}$ and $T_{\mathrm{OVI}} > T_{\mathrm{OV}} > T_{\mathrm{OIV}}$. Finally, the maximum measured temperatures (60–70 eV) are equal to the central electron temperature determined by Thomson scattering.[10] All these observations prove the efficacy of the ion measurements using the multichannel detector system in the VUV spectrum.

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